Hydrogen Safety Basics for Current and Planned Applications:

Presented by the NHA
to the U.S. DOE
DER Road Shows

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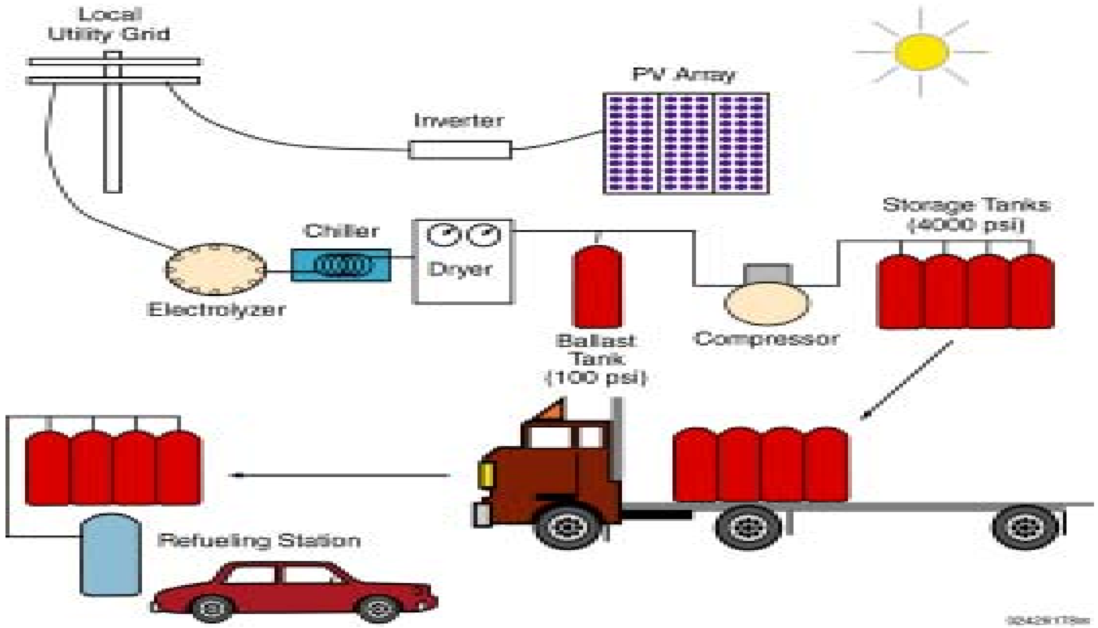
Hydrogen

- What is it?
- Where is it derived from?
- Why are we talking about it today?



Hydrogen Basics

- **Uses, Today and Future**
  - **Today: chemical processing, petroleum industry, fats and oils, metals, electronics, space flight, utilities, glass manufacturing, and others**
  - **Future: stationary power, portable power, and transportation.**
- **Production**
  - **Today, mainly through reformation of fossil fuels**
  - **Future, from renewables as well as fossil fuels with carbon sequestration**
- **Properties**
  - **Hydrogen is the lightest, most basic, abundant element**
  - **Properties are unique - must be treated appropriately**

Hydrogen and Power

- IC Engines
- Gas Turbines
- Fuel Cells

- Hydrogen can and will be used as a general fuel for a variety of applications, just like gasoline or diesel or natural gas.

Applications

- **Portable Power**
  - **Fuel cells with Hydride storage replacing batteries**
- **Stationary Power**
  - **Uninterruptible power supply**
  - **Remote communities**
  - **Clean customer power**
- **Transportation**
  - **Buses**
  - **Fleet vehicles**
  - **Cars**

Hydrogen Fundamentals

- **Energy Content: 60,958 Btu/lb – highest energy content of all fuels on a weight basis**
  - **This is why NASA uses hydrogen – they care a lot more about weight than volume**
  - **Energy content is about three times higher than gasoline, natural gas, and propane on a weight basis**
  - **Energy content is only about one third that of natural gas and about an eighth that of propane on a volume basis**
- **Flammability limits (in air): 4.1 v% - 74 v%**
- **Explosion limits (in air): 18.3 v% - 59 v%**

- **1 kg of H2 is equivalent to 1 gallon of gasoline**
- **380 ft.^{3} of Hydrogen equals 1 gallon of gasoline**

Markets and Growth

- Energy security
- Global markets for vehicles, aircraft, and electricity are estimated to grow by a factor of 10 over the next century
- 40% of the human race has no access to electricity
- Disruptions in electricity supply are growing
- Environmental concerns driving new technologies

Trends

- Energy Security
- Climate Change
- Public interest in renewable energy
- Distributed generation
- Zero or ultra-low emission vehicles to improve air quality

Outlook

- Competitive business strategies and competitive technologies provide robust setting
- Hydrogen vision
  - Hydrogen enables renewable energy use in mainstream of transportation
  - Obtain firm and usable power from intermittent renewable energy resources
- No environmental impact at point of use

Hydrogen… The Freedom Fuel^{SM}

Hydrogen, Methane, & Gasoline

Property	Hydrogen	Methane	Gasoline	Units
Molecular Weight	2.016	16.043	107	amu
Normal boiling point temperature	20.268	111.632	310 to 478	K
Critical pressure	12.759	45.387	24.5 to 27	atm
Critical temperature	32.976	190.56	540 to 569	K
Density at critical point	0.0314	0.1604	0.23	g/cm3
Heat of fusion	58.23	58.47	161	J/g
Heat of vaporization	445.59	509.88	309	J/g
Heat of combustion (low)	119.93	50.02	44.5	kJ/g
Heat of combustion (high)	141.86	55.53	48	kJ/g
Energy of density	8.49	21.14	31.15	MJ/litre
NTP – 1 atm and 20°C (293.5K)				

Hydrogen Production Today

- Industrial systems
  - Production
  - Transport
  - Storage
  - Use

Hydrogen production cost estimates

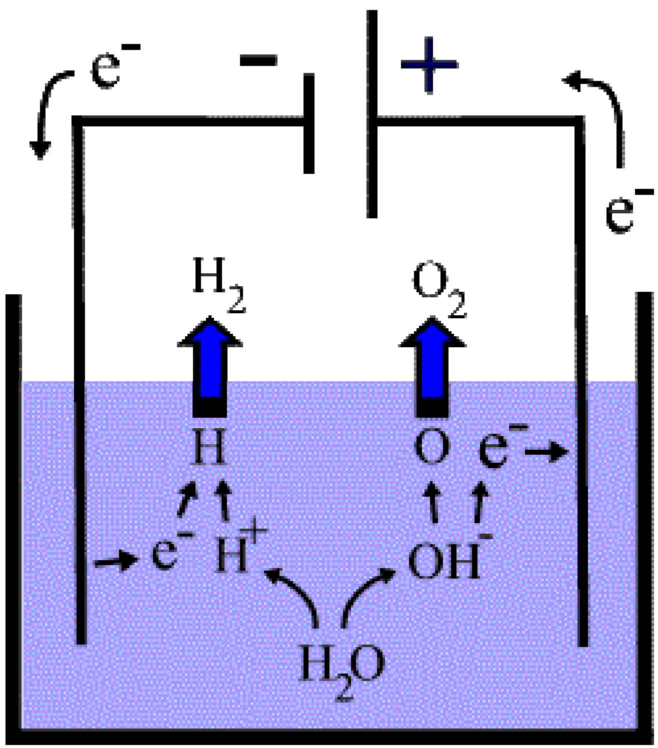
Type of facility	Fuel/Hydrogen price ($/GJ)
Petrol	3.5 (spot market $20/barrel) 7.9 (pre-tax) 31.0 (70p/litre)
Natural gas	1.8 (ave. wellhead 1990-99) 6.0 (wellhead Dec. 2000)
Steam methane reforming	5.4 (large plants) - 11.2 (small plants)
Partial oxidation	7.0 - 10.7
Coal gasification	9.9 - 11.6
Biomass gasification	8.7 - 13.1
Biomass pyrolysis	8.9 - 12.7
Methane pyrolysis	5.8 (C revenue) - 10.6 (No C revenue)
Steam methane reforming	6.0 (no CO_2 seq.) - 7.5 (with CO_2 seq.)
Wind-based electrolysis	11.0 (future 2010) - 20.2 (tech. 2000)
Solar-based electrolysis	24.8 (future 2010) - 41.8 (tech. 2000)

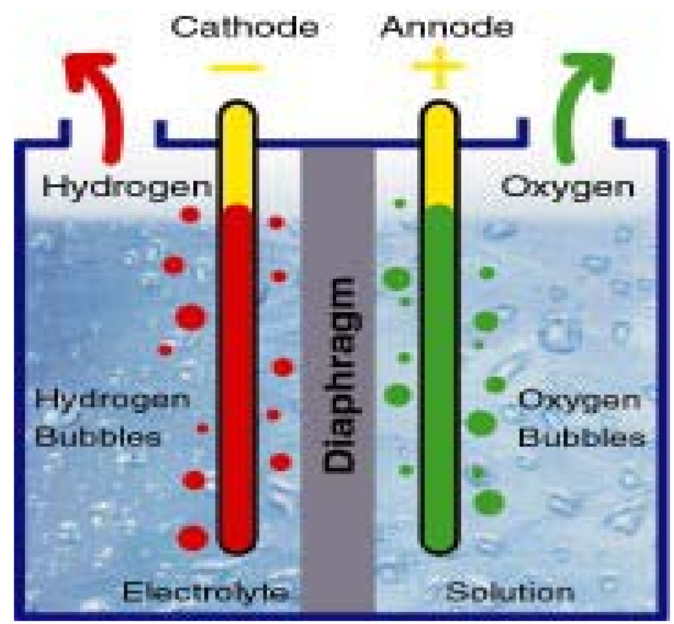
Source: Gregoire and Padro (1999), Mann et al. (1999), author

Electrolysis

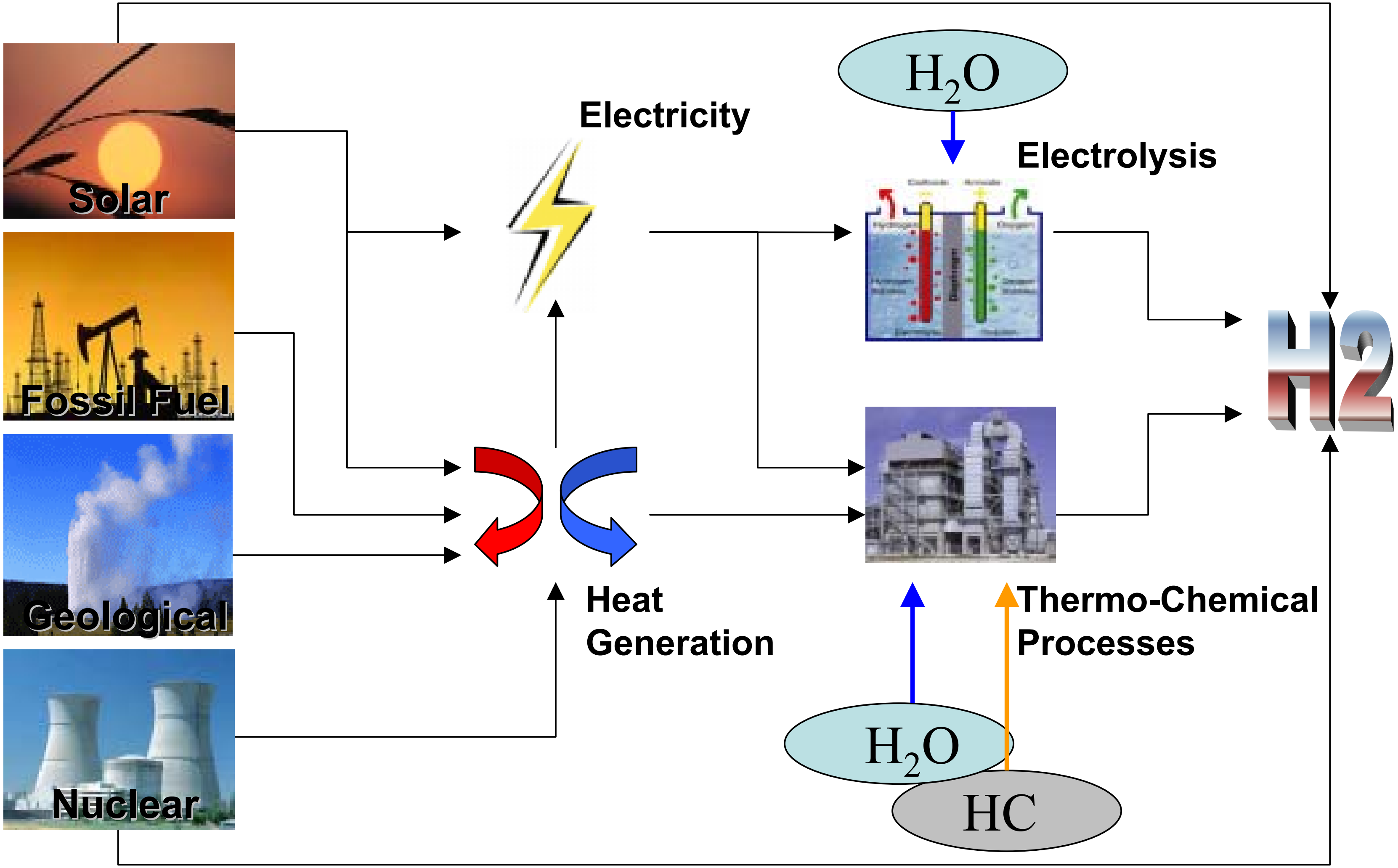
energy (electricity) + 2 H2O -> O2 + 2 H2

Electrolysis: Splitting water with electricity to produce hydrogen and oxygen:





Hydrogen Pathways



May 2003, Palm Springs, CA

Stuart electrolyzer will produce H2 fuel from wind power for city fuel cell electric vehicle (FCEV) buses

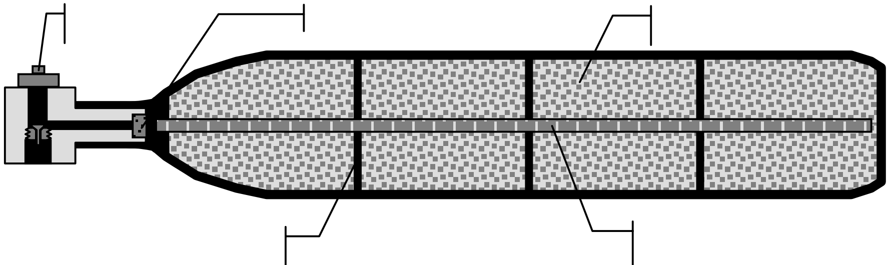
Electrolyzer and Hydrogen Costs

- To produce **I kg of gaseous hydrogen** by an electrolyzer requires about **55 kWh**
- If electricity costs are **3 cents/kWh**, the electricity costs would equal $14.00/mBtu, which is equivalent to gasoline costing **$1.60 per gallon.**
- With the cost and maintenance of the electrolyzer and related hydrogen storage and pumping system factored in, and assuming a non-high-volume electrolyzers the installed costs are in the range of $800/kW, an additional $8.00/mBtu brings the total cost of the gaseous hydrogen to about $22.00/mBtu, equivalent to gasoline costing **$2.60 per gallon**.
- If the **hydrogen is liquefied**, an additional $4.00/mBtus would be added, which makes the cost of liquid hydrogen about $28.00/mBtu, which is equivalent to gasoline costing **$3.00 per gallon** of gasoline.
- Additional savings can occur as a hydrogen internal combustion engine is about 25% more fuel efficient, and does not generate organic acids and carbon deposits, which contaminate the engine oil and reduce engine component life.

(Harry Braun, Hydrogen News)

Hydrogen Storage

Texaco Ovonic Hydrogen Systems, L.L.C.



Hydride Storage

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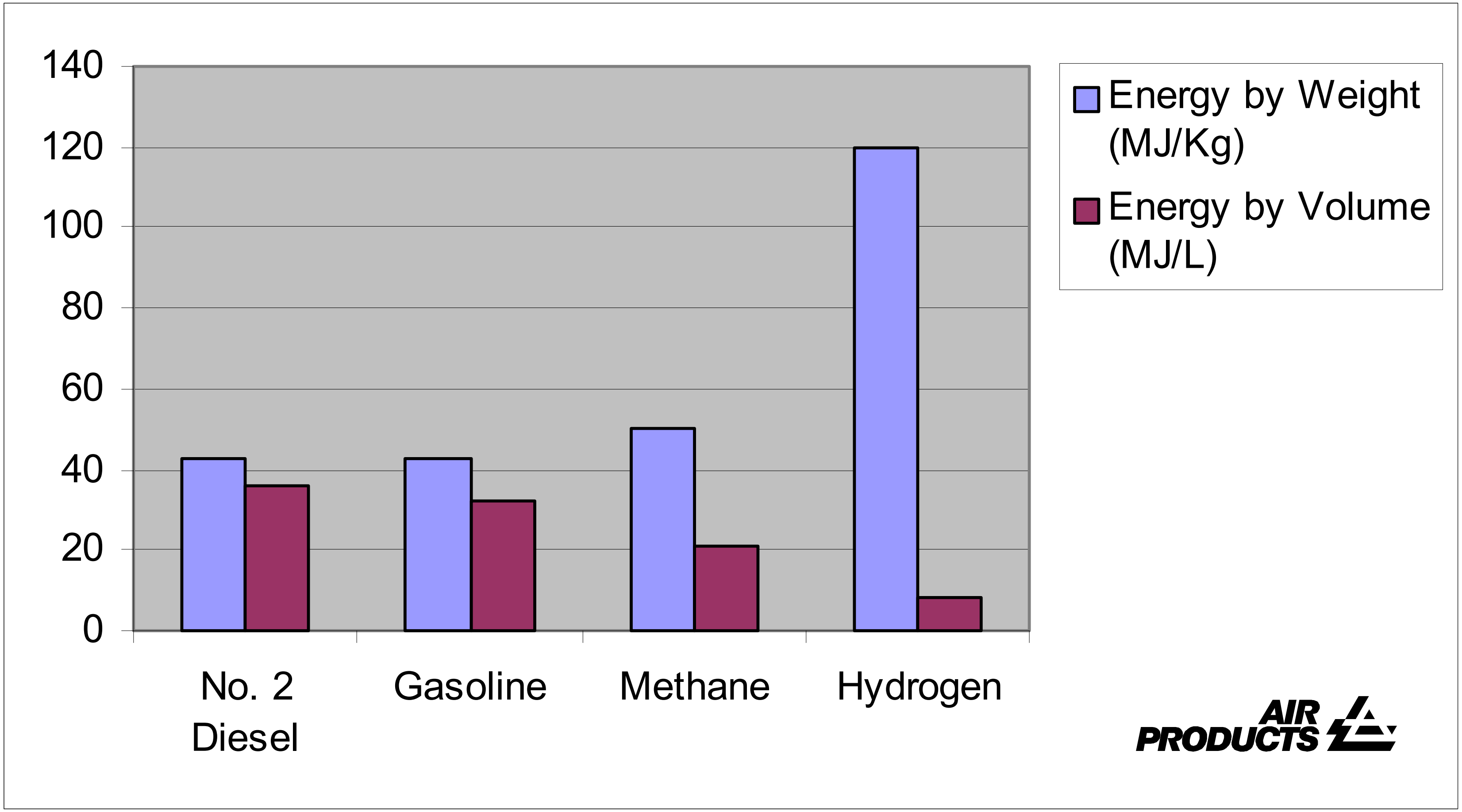
Hydrogen Storage



Increase Volumetric Density

- Compress the Gas (medium/high pressure)
  - **Increases Energy Requirement**
  - **Safety**
- Cool the Gas (liquid hydrogen)
  - **Increases Energy Requirement**
  - **Safety**
- Hydride storage with another material
  - **More complicated storage systems**
  - **Finding suitable materials**

Storage Challenge

Assume Hydrogen Vehicle gets 50 miles/kg of hydrogen and stores enough hydrogen for 300 miles:

$300 / 50 = 6$ kg H_2

	Fluid Vol	Total System	
	gallon	*gallon*	*lbs*
Atm. Pressure	> 19000	> 20000	> 15000
350 Bar Pressure	65	77	212
700 Bar Pressure	38	53	232
Liquid Storage	22	48	190
LT Metal Hydride	14	30	950
Chem. Hydride	21	72	315
Gasoline	15	17	94

Compare To Batteries

AIR PRODUCTS

Hydrogen Uses - Tomorrow

- Portable Applications
  - Laptop, cell phone, military uses
- Stationary Applications
  - Uninterruptible power supplies
  - Backup/premium power
  - Combined Heat and Power (CHP)
- Mobile Applications
  - Modified Internal Combustion Engines (ICE)
  - Fuel cell vehicles (buses, trucks, autos)

What are Codes and Standards?

- Documents that establish a basis for "technical communication"
- Provisions for assessing technology safety and performance
- The basis for "Building Construction Regulations" or other rules addressing public health and life-safety

Issues

- **Codes & standards are being developed in advance of, or in parallel with, hydrogen-fueled systems**
  - **Codes & standards development must be coordinated with technology development**
  - **Efforts should be devoted to R&D efforts to validate proposed standards (i.e., need data to support or validate proposed requirements)**
- **Coordination is vital**
  - **All applications involve production, transportation, storage, dispensing, and use of hydrogen**
  - **A large number of organizations are involved in generating codes & standards**

Codes, Standards, Regulations, and Recommended Practices

- Rule-making bodies in the US
  - About 20 major developers (excluding federal agencies such as EPA and DOT)
  - Nearly all is done using a consensus process
- Technical requirements called out in U.S. Model Building Codes
- Must be adopted by each jurisdiction to be "legal" and binding
  - Approximately **44,000** jurisdictions in the US
  - Federal, state, county, city or town

Key Codes & Standards

Component Technology	**Codes**	**Status**
Production	NFPA 70/ NEC/CEC ASME Boiler-Pressure Vessel Sec. VIII	mature mature
Transportation:	DOT 49 CFR	mature mature
Pipeline	NEC/CEC ANSI/ASME B31.1, B31.8	mature mature
Storage	NFPA 50 A: Gaseous Hydrogen NFPA 50 B: Liquid Hydrogen ASME Boiler-Pressure Vessel Sec. VIII	mature (1994) mature (1994) mature
Vehicle Refueling Stations	HV-3: Hydrogen Vehicle Fuel NFPA 52: CNG Vehicle Fuel HV-1: Hydrogen Vehicle Connector NGV1: NGV connectors	being developed base for HV-3 being developed base for HV-1
Hydrogen Vehicles	HV-3: Hydrogen Vehicle Fuel NFPA 52: CNG Vehicle Fuel HV-2: Gaseous Hydrogen Tanks NGV2: CNG Storage Tanks	being developed base for HV-3 being developed base for HV-2

U.S. Model Codes

- National Fire Protection Assoc. (NFPA)
  - NFPA 853 “Standard for the Installation of Stationary Fuel Cell Power Plants”
  - NFPA 70 (National Electrical Code)
- International Code Council (ICC) Ad Hoc Committee on Hydrogen
  - International Fire Code, International Mechanical Code, International Plumbing Code, International Fuel Gas Code, etc.

Existing Standards

- Hydrogen Codes, Standards, and Regulations Matrix
  - by application
  - includes contact information
  - includes status
- NFPA

The Matrix

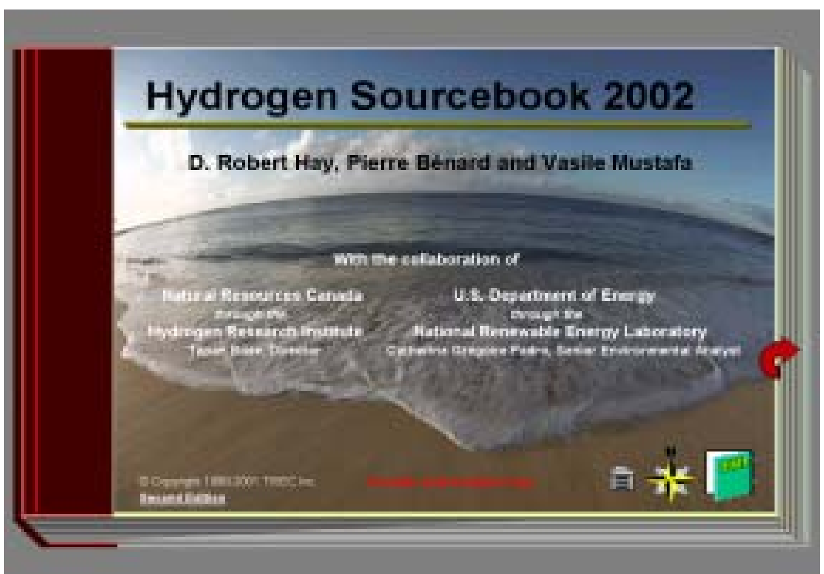
- Ongoing project to develop and maintain a list of relevant hydrogen codes and standards
- National and International
- Arranged by application
- Includes scope and contact information
- Updated regularly and posted in NHA’s Hydrogen Safety Report
  - **www.hydrogensafety.info**
  - **www.hydrogenus.org**

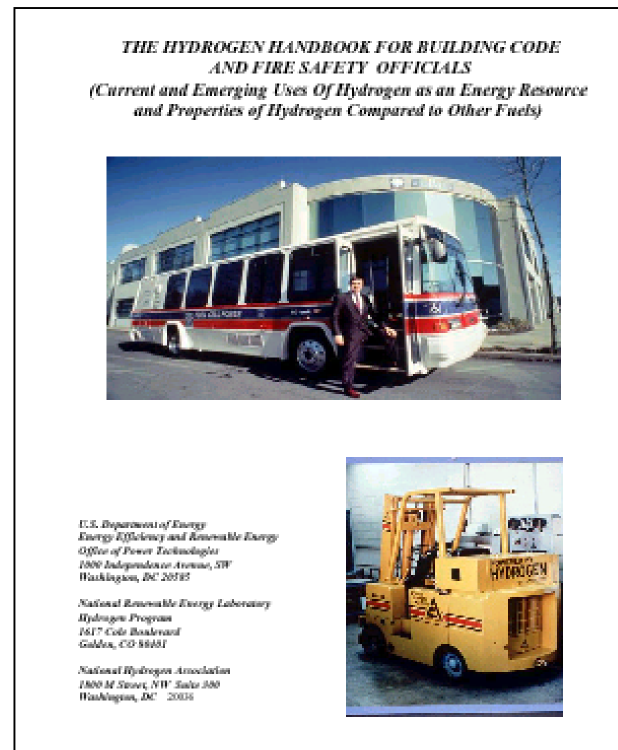
Resources for Permitting Officials

- The Hydrogen Safety Report
  - www.HydrogenSafety.info
- The Sourcebook for Hydrogen Applications
- Two New Permitting Guides
- ICC and NFPA Short Courses

Guidelines for Hydrogen Systems

- The Hydrogen Handbook for Building Code and Fire Safety Officials
- The Hydrogen Sourcebook





Hydrogen Sourcebook 2002

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Second Edition

Transfer Authorization Key

EXIT

Foreword

The Sourcebook identifies where the unique properties of hydrogen combine to create potential hazards and outlines effective methods for safe operation. It integrates societal perspectives and anticipates the directions they will take in the future. It helps the engineering and scientific communities meet safety obligations, both professional and in relation to the public. It shows other readers how the general expectations and requirements of the public for safety are met.

The Sourcebook includes references to available codes and standards and examples of how such codes and standards have been applied to hydrogen projects. It is revised periodically to incorporate new information as hydrogen technologies mature and as hydrogen projects are implemented. Such information can then be used to update existing codes and standards or as the basis for developing additional codes and standards.

Sponsored jointly by Natural Resources Canada (NRCan) through the Hydrogen Research Institute (HRI) at the University of Quebec at Trois Rivières and by the U.S. Department of Energy (DOE) through the National Renewable Energy Laboratory (NREL), the Sourcebook is promoted jointly by the Canadian Hydrogen Association and the National Hydrogen Association.

Foreword

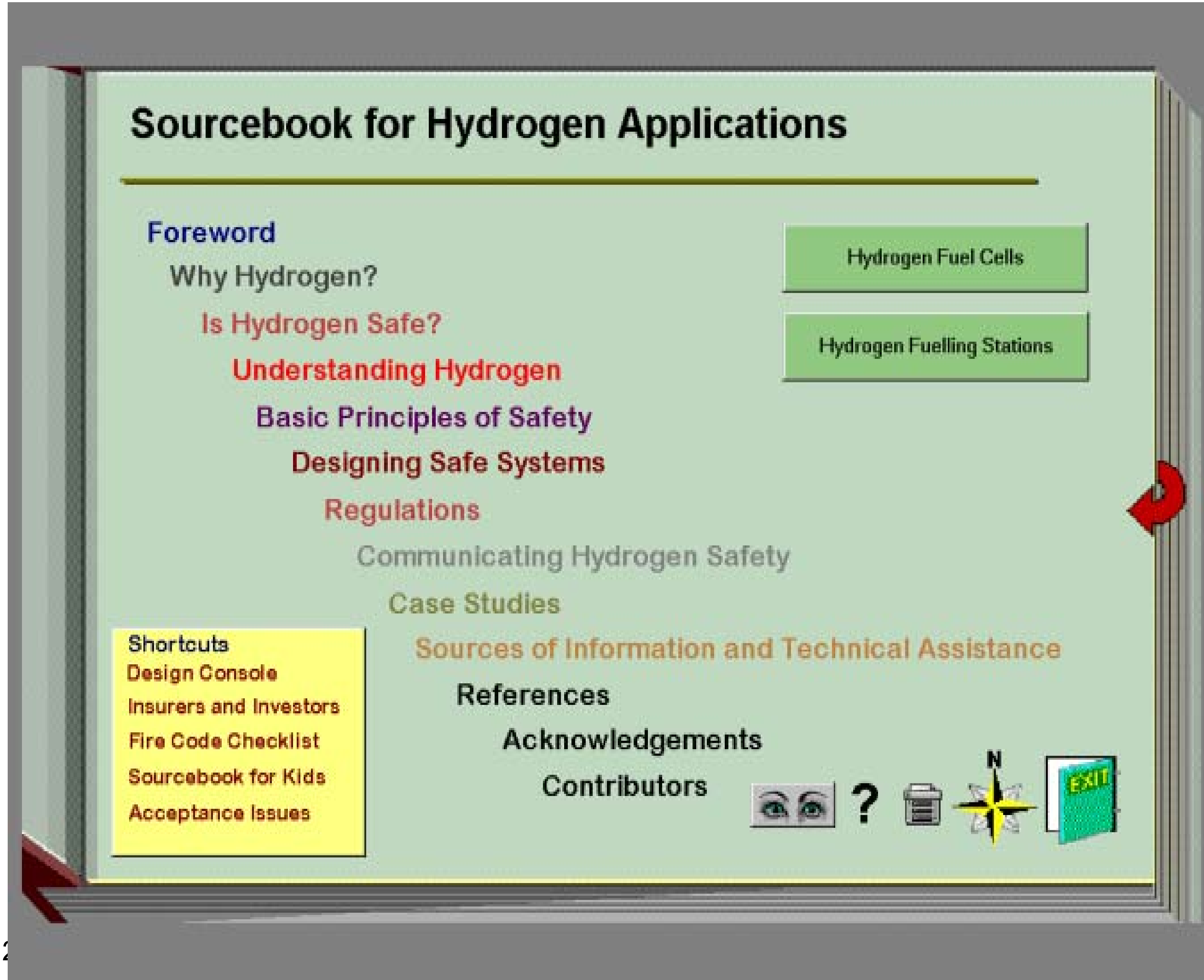
The Sourcebook describes some past and current uses of hydrogen, highlighting the safe record of hydrogen use in industrial applications. Increasing use of hydrogen as a feedstock for industrial processes will be augmented by the of hydrogen in new energy applications. The advent of new technologies, such as the fuel cell, will lead to widespread use of hydrogen as an energy carrier, particularly in the transportation sector. These emerging applications will require hydrogen system designs different than those established for industrial applications. For hydrogen vehicles, on-board hydrogen storage, hydrogen refueling systems, and prototype vehicle designs and propulsion technologies are being demonstrated. The Sourcebook provides information to facilitate designing, building, and operating hydrogen systems for these new applications.

Part of the intent of the Sourcebook is to transfer the experience and lessons learned in handling hydrogen safely over many years at the industrial scale to emerging uses of hydrogen that are smaller in scale, less centralized, and more accessible to the public.

Issues in this Sourcebook

- Inherent properties of hydrogen that give rise to risk
- Nature of risks produced by certain properties
- Methods available for risk aversion
- Risk aversion methods used in practice
- Techniques available for hazard identification, analysis and assessment

The Sourcebook will be updated periodically to reflect new knowledge and experience on using hydrogen safely in emerging applications. Comments and suggestions to improve the accuracy and usefulness of the Sourcebook can be sent directly to the authors from the Sourcebook if your computer is configured Internet access and email.


Sourcebook for Hydrogen Applications
Foreword
Why Hydrogen?
Is Hydrogen Safe?
Understanding Hydrogen
Basic Principles of Safety
Designing Safe Systems
Regulations
Communicating Hydrogen Safety
Case Studies
Sources of Information and Technical Assistance
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Acknowledgements
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Hydrogen Fuel Cells
Hydrogen Fuelling Stations
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Design Console
Insurers and Investors
Fire Code Checklist
Sourcebook for Kids
Acceptance Issues
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Inspecting a Hydrogen Installation

- Confinement
- Review Potential for Ignition
- Minimizing Consequences
- Review the Need for Detectors
- Safety Analysis
- Review Site-Specific Factors
- Personal Investigation

Checklist for Fire and Building Code Officials

Local building and fire code of officials are on the front line in protecting people and structures when dangerous goods are used.

In the case of new projects, the public interest is well served when a project promoter maintains close contact with local officials from a projects inception rather than seeking approvals once a project design is complete. In the case of applying technologies in a new field such as hydrogen this exercise can be a learning curve for both the project promoter and the local official.

Local regulators are familiar with the more common fuels. Through comparisons, building code officials can get an initial reference to begin their evaluation. Safe installation and operation of hydrogen systems involves two basic questions:

- Have steps been taken to ensure that the hydrogen has been safely confined?
- If hydrogen is released, have steps been taken to minimize any effects?

To answer these important questions, these key considerations will prove helpful:

Confinement	Review Potential for Ignition
Minimizing Consequences	Review the Need for Detectors
Safety Analysis	Review Site-Specific Factors
Personal Investigation	

Basic Principles of Safety

Inherently Safe Design

- **limiting quantity:** because code requirements vary dramatically with quantity, limiting the quantity of hydrogen stored and handled indoors is essential in minimizing the extent and consequences of accidental leakage. National and local building and fire codes stipulate the maximum allowable quantities of flammable liquids and gases for indoor storage, including the maximum allowable quantity of hydrogen that can be stored and handled in indoor facilities
- **hazards elimination:** regardless of quantity, all hydrogen systems and operations must be devoid of hazards by providing adequate ventilation, designing and operating to prevent leakage, and eliminating potential ignition sources. 80% of industrial hydrogen leaks ignite, indicating the importance of preventing hydrogen leaks (DTI 1997)
- **safety systems:** safety systems should be installed to detect and counteract or control the possible effects of such hazards as vessel failures, leaks and spills, embrittlement, collisions during transportation, vaporization system failures, ignitions, fires and explosions, cloud dispersions, and the exposure of personnel to cryogenic or flame temperatures. Undetected leaks were involved in 40% of industrial hydrogen incidents, indicating that hydrogen detection coupled with warning or active ventilation may be required (DTI 1997)
- **safe interface:** a safe interface must be maintained under normal and emergency conditions so at least two failures must occur before hazardous events could lead to personal injury, loss of life, or major equipment or property damage
- **positive isolation:** the source of hydrogen should be isolated when the system is not in use. The amount of hydrogen downstream of the point of isolation should be minimized

Basic Principles of Safety

Controls

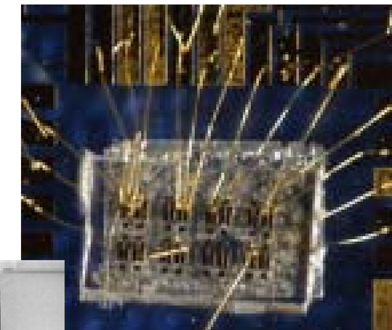
- **warning systems:** warning systems should be installed to detect abnormal conditions, measure malfunctions, and indicate incipient failures; warning system data transmission with visible and audible signals should have sufficient redundancy to prevent any single-point failure from disabling the system
- **periodic calibration** may be required for certain instruments
- flow controls: safety valving and flow regulation should be installed with response adequate to protect personnel and equipment during hydrogen storage, handling, and use
- **system safety features:** system and equipment safety features should be installed to automatically control equipment required to reduce hazards suggested by the triggering of caution and warning systems; manual controls within the systems should be constrained by automatic limiting devices to prevent overranging

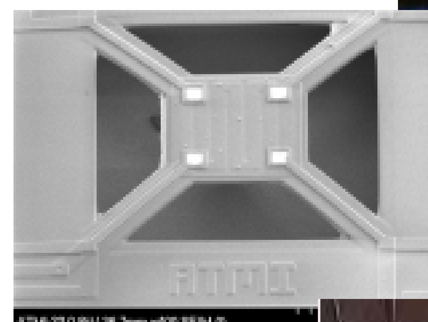
Fail-safe Design

- **verification:** equipment appropriately rated for hydrogen should be used; if certified equipment is not available, the equipment, power, and other system services must be verified for safe performance in the design and normal operational regimes
- **fail-safe design:** any failure that creates a risk of potentially hazardous conditions must cause the system to revert to conditions that will be safest for personnel and that have the lowest potential for property damage
- **redundant safety:** redundant safety features must be designed to prevent a hazardous condition from arising when a component fails

Detection

- Sensors
  - Safe, reliable, cheap sensors being developed
  - Placement is important
- Odorants
  - Diffusion/dispersion matching is difficult
  - Poison to fuel cell?





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